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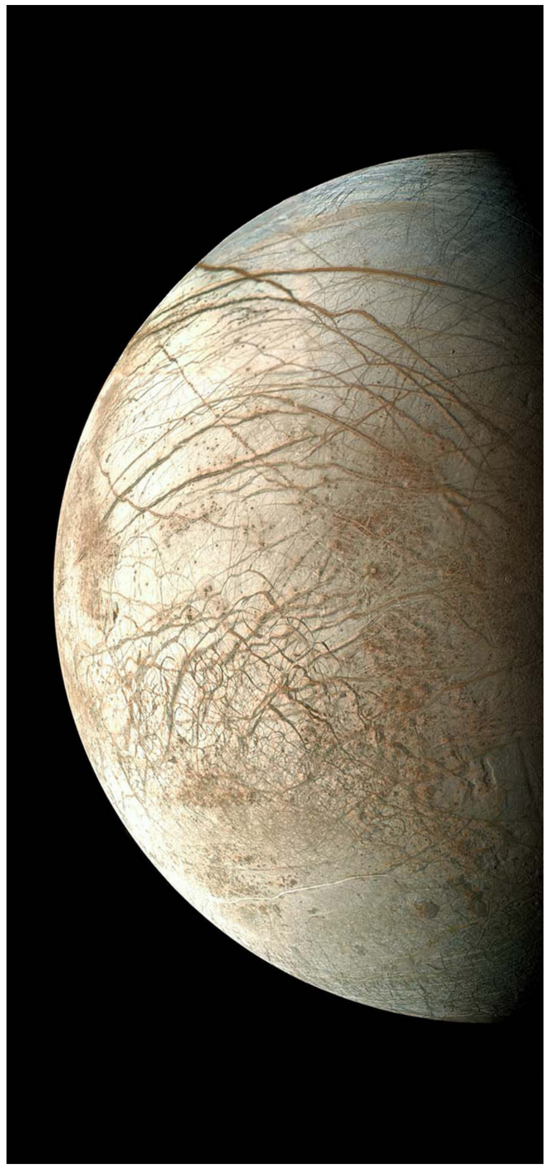
# Assessment of Alternative Europa Mission Architectures

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# 1. Executive Summary

The purpose of this study was to assess the science merit, technical risk and qualitative assessment of relative cost of alternative architectural implementations as applied to a first dedicated mission to Europa. The objective was accomplished through an examination of mission concepts resulting from previous and ongoing studies. Key architectural elements that were considered include moon orbiters, flybys (single flybys like New Horizons and multiple flybys similar to the ongoing Jupiter System Observer study), sample return and *in situ* landers and penetrators.

Science merit was assessed relative to the 2007 Europa Explorer (EE) Science Definition Team (SDT) science objectives, which focus on global characterization. An orbital remote observation type of mission is a natural fit to global characterization rather than the single location of a lander or limited coverage of a few, even many, flybys. The most recent 2007 EE Flagship study concluded that a dedicated moon orbiter would be the lowest cost and risk architecture that would fully achieve all of the science objectives identified by the SDT. This is consistent with the conclusions of previous studies.

An examination of multiple and single flyby missions indicates poor science value when compared to a dedicated moon orbiter. A single flyby mission would yield very little in terms of Priority 1 science objectives. A spacecraft in orbit around Jupiter that makes multiple flybys past Europa, similar to the recently defined Jupiter System Observer mission with more than 6 low-altitude (100–200 km) flybys of Europa, would provide significant science for some of the key objectives; however, it falls short of achieving most top-priority science objectives. Because flyby missions would not be in orbit around Europa and thus spend much less time in the near vicinity of Europa, even the most favorable implementation would accomplish less than 50% of the Priority 1 science objectives.

While landers have the potential to return significant new science from Europa's surface, the science results would be limited to only a single site. As a result, a lander-only mission falls far short of achieving Priority 1 science objectives. In addition, due to the uncertainties in today's limited understanding of Europa's surface features, a first dedicated mission at Europa consisting only of a single lander would be characterized as having high risk. Data from a predecessor Europa orbiter would greatly reduce the risk for subsequent implementation of an *in situ* mission.

The combination of a dedicated moon orbiter and a lander would clearly provide more science return than an orbiter alone, but it would require more resources (fiscal and possibly technical) than are currently anticipated to be practical in the near future.

The study concludes that a dedicated moon orbiter would provide the greatest science value at lowest risk and cost for a first dedicated mission to Europa. This conclusion is consistent with the conclusions of previous studies.

## 2. Background

Over the last decade there have been a number of mission and system studies that have defined science objectives, mission architectures and implementation approaches applicable to a dedicated mission at Europa. Over that period of time, variations in the programmatic and technical environments have significantly influenced the results. For example, the Europa Orbiter (EO) study of 2001 had a severe pressure on cost and flight time. This resulted in a ~$1.2B mission with less than 30 kg of science instrumentation delivered by a direct Earth-to-Jupiter trajectory into Europa orbit. This was followed in the 2002–2005 timeframe with a focus on breakthrough capability for solar system exploration (i.e., nuclear electric propulsion and power) and expanded goals for Jupiter system science (multiple destinations: Ganymede, Callisto, Europa). This resulted in the Phase A conceptual design of a nuclear electric Jupiter Icy Moons Orbiter (JIMO) mission that was estimated to cost greater than $10B. In the current era, following the success of Cassini/Huygens, serious consideration is being given to preparing for the next outer planet flagship mission in a fiscally constrained environment. Current Flagship Mission studies have targeted a total mission cost in the $2–3B range. This assessment of alternative architecture options was undertaken to ensure that the science value of a Europa flagship mission would be maximized relative to the currently defined science objectives at an acceptable level of risk.

The approach to assessing alternatives has been to review what has been learned to date from past studies and evaluate those results in context of the currently evolved science objectives and programmatic/technical constraints. The 2007 EE science objectives resulted from over a decade of community input and debate. The resulting objectives focus on understanding the global aspects of Europa.

The balance of this report provides an historical summary of previous studies as well as an assessment of alternative Europa mission architectures. A summary of conclusions is provided at the end of this document.

## 3. Summary of Historical Europa Mission Concept Studies

In the last decade (spanning from April 1996 to present) more than a dozen Europa Mission concepts have been studied at JPL to varying degrees. They are listed in chronological order in Table 1. Brief highlights and references from those studies are included. This section provides a summary of the studies in this table.

**Table 1: Historical Europa Mission Studies**

| Study Name | Power Source | Key Features | Ref |
|---|---|---|---|
| Europa Orbiter (1996) | RPS, Solar | Series of studies by Team X of simple, low-cost Europa orbiter mission. Looked at solar and RTG options | 1 |
| Europa Orbiter; Pluto S/C Option Study (1996) | RPS, Solar | Study to look at adopting new technologies being used on then-current Pluto mission study. Included RTG, AMTEC and solar options | 2 |
| Europa Sample Return (1996) | Solar | Study for potential Discovery proposal to fly Stardust-type capture and return of sample blasted from Europa surface by small impactor. | 3 |

| Study Name | Power Source | Key Features | Ref |
| --- | --- | --- | --- |
| Europa Orbiter, All Solar (1997) | Solar | Delta-V Earth Gravity Assist trajectory, Titan IV (SRMU)/Centaur, payload 42 kg | 4 |
| Europa Orbiter, All Solar (1998 IOM) | Solar | Revisit of 1997 All Solar study. Venus-Earth-Earth Gravity Assist (VEEGA) trajectory, STS/IUS, payload 20 kg, mass margin −15 kg, solar array 235 kg | 5 |
| Europa Orbiter (2001) | RPS | Direct trajectory, science payload 27 kg | 6 |
| Europa Orbiter Alternative Missions Study (2001) | RPS | Various trajectories, many options | 7 |
| Europa Orbiter Competitive (2002) | RPS | Look at low cost Europa orbiter mission for potential New Frontiers proposal | 8 |
| Jupiter Icy Moons Tour (2002) | Reactor | Flagship Mission, science payload 490 kg | 9 |
| Non-Fission Icy Moons Tour (2002) | RPS | Two S/C mission to all Galilean satellites, science payload 273 kg, plus two landers (Callisto and Ganymede) | 10 |
| Jupiter Icy Moons Orbiter (2005) | Reactor | Flagship Mission, science payload 1,500 kg | 11 |
| Europa Geophysical Explorer (2005) | RPS | VEEGA trajectory, science payload 153 kg plus additional margin 853 kg (additional 853 kg probably too optimistic, ~340 kg is a more likely figure) | 12 |
| Europa Explorer (2006) | RPS | VEEGA trajectory, science payload 180 kg plus unallocated margin of 340 kg | 13 |
| Europa Explorer Solar Array Feasibility Study (2006) | Solar | Attempt at an all-solar implementation of Europa Explorer science mission; found to be not practical. | 14 |
| Enhanced Europa Geophysical Explorer (2006) | RPS | Broad architectural assessment for single orbiter. VEEGA trajectory, science payload 150 kg plus additional margin 340 to 1200 kg (additional margin due to advanced RPS, larger LV and later launch dates) | 15 |
| 2007 Europa Explorer Flagship Study | RPS | NASA-funded flagship study. Numerous architectures considered with focus on single orbiter. VEEGA trajectory, ~205 kg science payload (includes contingency), mass margins 982 kg including 185 kg “unallocated” margin | 16 |
| 2007 Solar Europa Feasibility Study | Solar | Investigation of an all-solar implementation of Europa Explorer science mission; focused on achieving floor science objectives of 2007 EE Study. | 17 |

### 3.1 Europa Orbiter (1996)

This represents the first study performed by Team X to investigate a mission to Europa. The initial study was performed in April of 1996 aimed at developing a very simple, single instrument (radar) mission to orbit Europa. Options explored included solar power and use of one half of a General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS RTG) to meet low power requirements (less than 150W). A series of updates to the original study were performed through May of 1996, ending up with design using one full GPHS RTG and incorporating technologies assumed for a concurrent Pluto mission study. Further options were investigated including benefits of Solar Electric Propulsion (SEP) (not found to be of significant value).

### 3.2 Europa Orbiter; Pluto S/C Option Study (1996)

The purpose of this study was to further develop the Europa mission concept using the then-current Pluto spacecraft hardware design, taking full advantage of the advanced technologies being considered for that mission. Three design options were investigated: one using a single GPHS RTG, one using the Alkalai Metal Thermoelectric Converter (AMTEC) RPS then in development, and a solar option.

### 3.3 Europa Sample Return (1996)

This study evaluated a possible candidate for a Discovery-class mission that would use the Stardust spacecraft architecture to capture and return a surface sample from Europa. The concept would have delivered a projectile to the surface of Europa to eject a plume through which the spacecraft would fly at ~ 50 km altitude, capturing plume particles in aerogel for return to Earth. Mission duration was estimated to be ~10 years. The mission was envisioned to be solar powered, using a “hibernation” mode to conserve power at large sun ranges.

### 3.4 Europa Orbiter, All Solar (1997)

This study was performed by Team X in 1997 to develop a point design for an all-solar mission to Europa. The study looked at a launch in late 2004 on a Titan IV launch vehicle followed by a 4.6-year flight to Jupiter using an Earth gravity assist. Wet mass for this concept was 3530 kg, leaving a margin of 1952 kg for launch on the Titan IV. Payload mass was 42 kg (including a 15-kg surface package). Solar arrays were estimated at 159 kg.

### 3.5 Europa Orbiter, All Solar (1998 IOM)

This IOM reassessed the feasibility of designing an all-solar mission to Europa. The work revisited the previous study performed by Team X in June 1997 by reexamining some spacecraft assumptions and by considering the possible use of a Shuttle with an Inertial Upper Stage. The combination of these two assumptions with the Team X study conclusions resulted in some increased performance as compared to the Team X conclusion but not nearly enough to change the ultimate conclusion that a Titan IVB launch vehicle would be required to attempt the mission without using an RPS for a power source. Launch date for this reanalysis was October 2005. Launch mass was decreased to 2925 kg and payload allocation was reduced to 20 kg. Solar array mass was sized to accommodate 135 W of extra heater power to avoid the need for Radioisotope Heater Units (RHUs). Even with the reduced capability and lower flight system wet mass, the study was not able to achieve a positive margin for launch on the Shuttle.

### 3.6 Europa Orbiter (2001)

This was the first rigorously developed point design for a Europa mission. The development effort spanned several years and resulted in a Radioisotope Power System (RPS)-based flight system design (Figure 1) constrained to a direct Earth-Jupiter trajectory. The science mission duration of 30 days in Europa orbit was determined by the SDT to be the minimum time required to meet the science objectives. This concept accommodated a modest science payload of 27 kg. Wet mass of this design was~1790 kg and power was to have been provided by two GPHS RTGs. Driving science requirements included the category 1A objectives defined by the SDT:

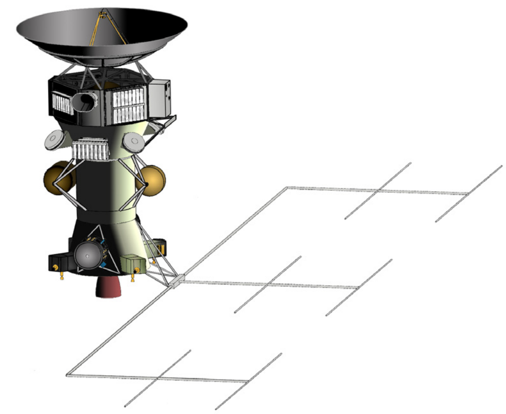

**Figure 1. 2001 Europa Orbiter Flight System.**

- Determine the presence or absence of a subsurface ocean
- Characterize the 3D distribution of any subsurface liquid water and its overlying ice layers
- Understand the formation of surface features, including sites of recent or current activity, and identify candidate sites for future lander missions

The work performed in this study provided insights into the issues associated with implementation of Europa missions, including a full assessment of the radiation environment and technologies for accommodating operations in that environment.

### 3.7 Europa Orbiter Alternative Missions Study (2001)

This report assessed alternative approaches to the EO mission in an effort to investigate lower cost options. Primary trades investigated included; an assessment of trajectory options including both direct and indirect trajectories, flight system trades between the EO baseline and minimum mass implementations, and endgame science mission options at Europa including an assessment of orbiters and flyby missions. Mission architectures were developed that addressed subsets of the full EO science objectives based on temporal or spatial observations. Alternative architectures resulted in some cost savings, but at the expense of full science.

### 3.8 Europa Orbiter Competitive (2002)

This study investigated the possibility of developing a simple, low-cost (less than $1B) mission to Europa that could potentially be developed as a New Frontiers proposal. The mission was envisioned to use a single GPHS RTG for power and had a limited payload of six instruments: a radar and a five-element Europa Integrated Science package totaling ~17 kg. Mission length was 30 days in orbit.

### 3.9 Jupiter Icy Moons Tour (JIMT) Studies (2002)

Three mission concepts were studied by independent teams: A reactor-powered mission employing a single launch vehicle to deliver the flight system to space, a second reactor-powered option employing multiple launches to low-Earth orbit (LEO) and using on-orbit assembly techniques to construct the final flight system, and a third non-reactor–powered option consisting of one or more flight systems to meet the same science objectives. All mission studies were completed as directed.

### 3.9.1 Reactor Options

The reactor options fall into a unique category. They would utilize nuclear fission power systems and advanced ion propulsion to enable exploration of multiple targets in a single mission. These studies also offered greatly enhanced science payload mass and power. The single launch option of the JIMT study had a science payload allocation of 490 kg and a total flight system launch mass of 21,000 kg. It would have been delivered to LEO by a single Delta-IVH launch vehicle, from which point it would have activated its nuclear electric propulsion (NEP) system to spiral out to its Jupiter trajectory. The on-orbit assembly option was similar to the single launch option, but would have launched the fuel tank and science module first on a heavy Evolved Expendable Launch Vehicle (EELV), to be followed by a shuttle launch of the power and propulsion module which would have been mated to the previously launched elements in LEO. Large solar arrays were to be used to provide solar-electric propulsion for the initial spiral-out from LEO. Total launch mass of this option would be about 23,000 kg with a payload allocation of 500 kg.

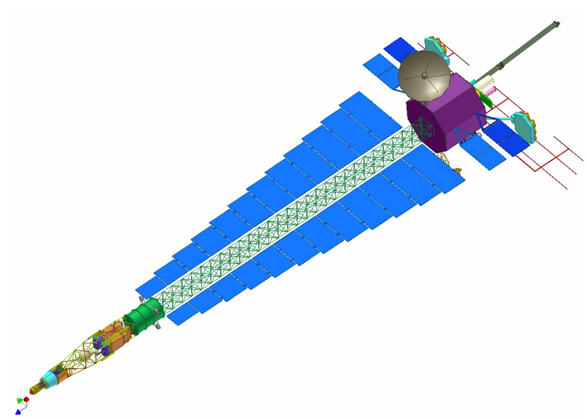

**Figure 2. JIMT Single Launch Option.**

### 3.9.2 Non-Reactor Option

The non-reactor JIMT team was asked to create a mission concept that (a) would achieve, as a minimum, the Europa Orbiter Level 1 science objectives at Europa, Ganymede and Callisto, (b) could be implemented for launch by the end of the decade, (c) would cost not more than $4.5B, and (d) could be implemented without use of fission power. A large number of possible mission architectures was quickly reduced to five options for further study:

1. Jupiter orbital flotilla consisting of three identical spacecraft in orbit around Jupiter with multiple flybys of the three ice moons.
2. Icy moon flotilla consisting of a dedicated orbiter to each of the three icy moons.
3. Single large cruiser that would sequentially orbit each of the three icy moons for several weeks before moving on to the next.
4. Dual identical cruisers that would sequentially orbit each of two of the moons.
5. SEP/Radioisotope Electric Propulsion (REP) mother ship that would deliver a dedicated orbiter to each of the icy moons.

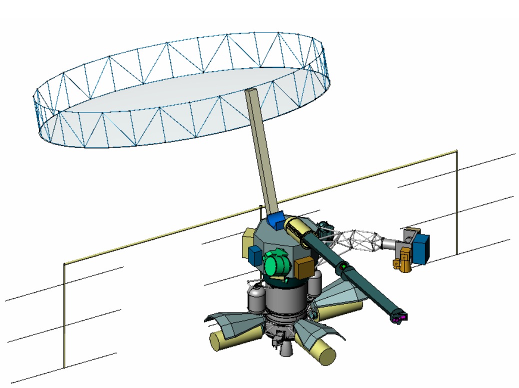

**Figure 3. Non-Fission Option Orbital Configuration.**

The fourth option was chosen for development in the study. Dual, identical twin spacecraft (Fig. 3) would be deployed to the Jovian system to provide full redundancy for Europa. Cruiser 1 would be deployed to Callisto first, for 12 weeks of detailed mapping and deployment of a small lander. It would then be flown into orbit around Europa for Europa science and end of mission. Cruiser 2 would be deployed to Ganymede into a 10-week mapping orbit, then into orbit around Io for its end of mission. Redundancy for Europa would be provided by phasing Cruiser 2 flight time to allow diversion to Europa in event of problems with Cruiser 1.

The flight system design took advantage of existing and a few high-value new technologies to lower mission risk and cost. A 100-kW SEP system (beginning of life power) with NASA Evolutionary Xenon Thrusters and Square Rigger Photovoltaic solar arrays was baselined. The Science Mission Module would use radiation-hard avionics and three 250-W advanced RPSs. A sixteen-instrument, 273-kg payload was accommodated on each spacecraft. One 132-kg lander was also carried on each spacecraft for delivery to Callisto and Ganymede. Landers each carried six instruments.

## 3.10 Jupiter Icy Moons Orbiter (JIMO)

The JIMO project mission and flight system designs evolved directly from the single launch option of the JIMT study. Requirements expanded over the course of this study and both the flight system and payload allocation grew. The payload allocation for JIMO (Fig. 4) was 1,500 kg and the total launch mass was more than 36,000 kg. While the capabilities of the JIMO flight system would have revolutionized the approach to outer planets science missions, the estimated cost of developing the project was deemed too large; the programmatic priorities changed at Headquarters, and, after successfully completing Phase A, further effort was indefinitely deferred. For this reason the Jupiter Icy Moons studies will not be included in further assessments contained in this report.

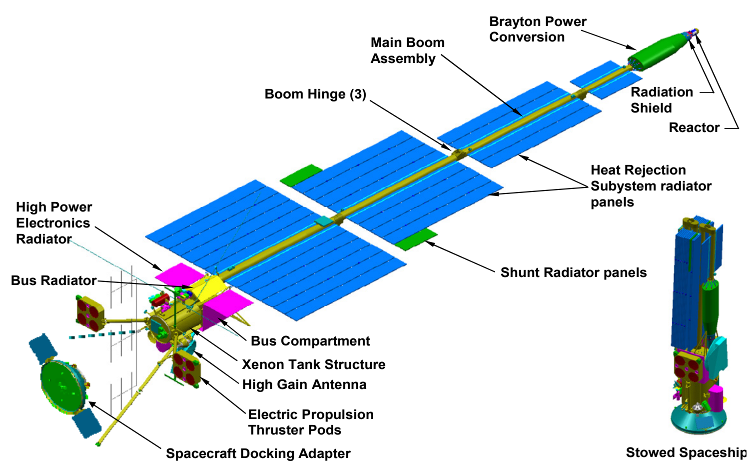


**Figure 4. JIMO Configuration.**

## 3.11 Europa Geophysical Explorer (2005)

The Europa Geophysical Explorer (EGE) study, funded by NASA's Planetary Program Support task and the NASA RPS Mission Systems Engineering Office, returned to the concepts of inner solar system gravity assists and conventional chemical propulsion for a mission to Europa, using radioisotope power in the form of the newly developed RPSs. This study made use of a Venus-Earth-Earth Gravity Assist (VEEGA) trajectory to increase delivered mass over previous studies, resulting in a launch mass capability of ~7230 kg using a Delta IVH launch vehicle. A payload allocation of 150 kg was baselined. The payload was sufficient to meet all newly defined science objectives in a Europa orbital mission phase of 30 days.

### 3.12 Europa Explorer (2006)

The EE study, which was internally funded by JPL, involved a detailed analysis of a Europa orbital mission. It took advantage of recent technology developments and additional knowledge gained from past studies to develop a highly capable mission aimed at meeting current science objectives for Europa. This study developed a flight system (Fig. 5) with a wet mass of 6988 kg. Science payload allocation was ~180 kg, with an additional 340 kg "unallocated mass" potentially available for a lander or other science payload. The orbital phase of the mission was extended to 90 days in collaboration with the science team. The improvements over past study results were made achievable by significant advances in radiation-hardened component technologies, now-proven larger launch capabilities and well-established gravity assist trajectory options, and better characterized radiation environment around Europa. The concept relies on traditional chemical propulsion system (similar to Cassini and Galileo), Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs - as are to be employed by Mars Science Laboratory) and a real-time continuous data downlink.

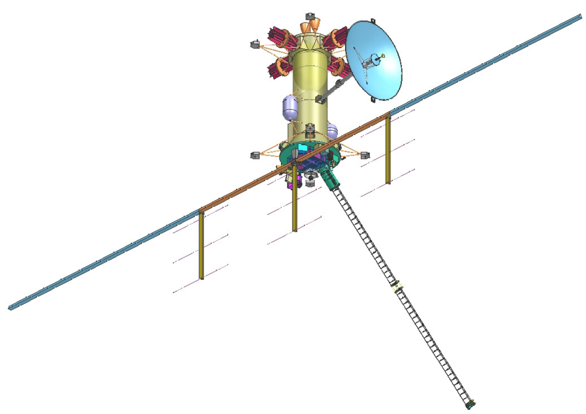

**Figure 5. EE Orbital Configuration.**

### 3.13 Enhanced Europa Geophysical Explorer (2006)

The Enhanced Europa Geophysical Explorer (EEGE) study was performed in 2006 to update the original EGE concept and assess the mass impacts associated with using different existing and advanced radioisotope power systems. Also studied were the mass implications associated with choosing different launch dates, interplanetary trajectories, and launch vehicles. The output was a detailed trade space analysis that could be used to assess the enabling and potentially cost-saving capabilities of using advanced RPS systems for a Europa mission. As expected, mass and power gains were realized when using the most advanced RPSs and most capable launch vehicles. EEGE was funded by NASA's RPS office.

### 3.14 Europa Explorer Solar Array Feasibility Study (2006)

This study, which was internally funded by JPL, evaluated the potential for replicating the EE 2006 science mission using solar power instead of RPSs. The study looked at the issues involved with the use of solar arrays in the Europa environment, considering radiation degradation and low solar intensity. The very large size of the arrays needed to accommodate Europa eclipses and the large gimbals and reaction wheels needed for this implementation led to the conclusion that this approach was not practical within the EE mission orbital constraints.

### 3.15 Europa Explorer Flagship Study (2007)

The NASA-commissioned 2007 EE Flagship Study has recently been completed. For this study NASA appointed an SDT to develop science objectives in light of the advances in understanding made by the JIMO SDT and refined by subsequent studies and science advisory groups. A further development of the mission and flight system developed in the EE 2006 study, it accommodated 205 kg of science payload (maintaining 185 kg of unallocated margin) while refining the design (lower telecom power and sequencing of instruments) to allow reduction in the number of MMRTGs from eight to six. This study looked at a baseline implementation, achieving all of the objectives of the Europa SDT, and a floor mission that would achieve many of the SDT objectives at a lower total mission cost. Results were thoroughly reviewed by NASA-appointed independent science and technical, management and cost panels.

### 3.16 Solar-Powered Europa Orbiter Design Study (2007)

In parallel with the 2007 EE Study, a solar-powered Europa Orbiter Design Study, which was internally funded by JPL, was carried out to take another look at the possibility of using solar arrays to provide power to a Europa mission (Fig. 6). This fairly high-level study directly addressed the issues raised by the 2006 EE solar study by changing the science orbit at Europa to one with continuous illumination, thus greatly reducing the excess solar array area needed to accommodate frequent eclipses and enabling a configuration with fixed solar arrays. A single-session Team X study was performed to evaluate the feasibility of such a mission that could accommodate the floor science objectives as defined by the 2007 EE SDT. Preliminary results indicate that such a mission might be viable and warrants further study.

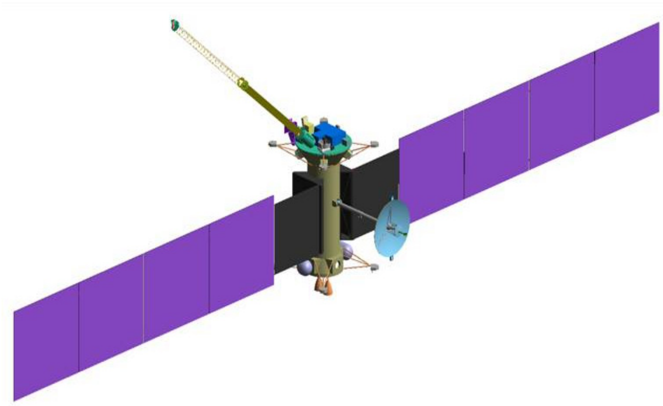

**Figure 6. Solar Powered Europa Concept.**

### 3.17 Europa Lander Studies

In addition to the orbital missions studied over the last decade a number of studies have been carried out to investigate designs for Europa landers. These studies have looked at a wide range of capabilities ranging from simple penetrators to very capable landers with cryobots and submarine vehicles capable of exploring the Europan ocean. A summary of the design parameters for some of these past studies is presented in Table 2.

None of the Europa mission studies ended up baselining a lander vehicle as part of their mission architecture. Each mission study concluded that the accommodation of a Europa landed package of some form would provide significant science above that required to meet the science objectives. The reluctance to baseline such a package has come from a combination of the estimated cost and risk impact that such an auxiliary element would have on the overall mission.

### 3.18 Science Goals and Objectives

The mission and spacecraft conceptual designs for exploration of Europa have significantly progressed over the years in detail and maturity. In parallel, the Europa science goals and objectives have evolved into a more comprehensive set of Priority 1 Objectives. Over the last decade several key advisory groups have considered and recommended sets of science objectives

**Table 2. Past Europa Lander Studies (ref. 18).**

| Study title | Wet | Dry | Propellant | Landing | Power |
|---|---|---|---|---|---|
| Europa Lander (Baseline, 1997) | 886 kg | 338 kg | 549 kg | Soft | AMTEC RPS |
| Europa Lander (Microtech, 1997) | 828 kg | 279 kg | 549 kg | Soft | AMTEC RPS |
| Europa Pathfinder (2001) | 221 kg | Solid Propulsion | | Airbag | Battery + RHU |
| Europa Lander (1999) | 487 kg | 228 kg | 259 kg | Soft | AMTEC RPS |
| Europa Lander + Cyobot+ Submarine (1998) | 1502 kg | 646 kg | 856 kg | Soft | AMTEC RPS |
| Scout Lander (2000) | 3451 kg | 1502.1 kg | 2340.2 kg | Multi | AMTEC ARPS |
| Europa Impactor (2000) | 4×7kg | N/A | N/A | Impactor | Battery |
| Cadmus (Ga Tech, 2004) | 558 kg | 248 kg | 310 kg | Soft | MMRTG |
| EGReSS (Ga Tech, 2004) | 1575 kg | 440 kg | 1135 kg | Soft | MMRTG |
| JuIcy (Ga Tech, 2004) | 1211 kg | 511 kg | 700 kg | Soft | Undefined RTG |
| Europa Surface Science Package (2004) | 379 kg | 44 kg | 143 kg | Soft | Modified RTG |
| Jupiter Icy Moons Lander (2006) | 390 kg | 362 kg | 22 kg | Soft | Battery |

for the exploration of Europa (Table 3). The lineage of Europa science objectives traces back to the EO SDT, whose "Group 1" (highest priority) and "Group 2" (second priority) objectives were subsequently endorsed by the NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System, and then by the National Research Council's Solar System Exploration Survey ("Planetary Science Decadal Survey"). The Decadal Survey explicitly stated that a flagship-class mission should address both the Europa Orbiter Group 1 and Group 2 objectives, in addition to Jupiter system science during its Jupiter orbiting phase.

Subsequent to the recommendations of the Decadal Survey, the JIMO SDT expanded the scope of Europa objectives and included additional objectives relevant to the whole Jupiter system. Following NASA's indefinite postponement of the ambitious JIMO mission, the Outer Planets Assessment Group honed the objectives for Europa exploration. These objectives were iterated by the Europa Focus Group of the NASA Astrobiology Institute, and then codified by OPAG [2006] in its Scientific Goals and Pathways document. This codification was subsequently reflected in the 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate. The EE 2007 SDT reviewed and updated the 2006 objectives and relative priorities for use in their study. It is these Europa objectives that form the basis of the latest EE mission studies.

**Table 3. Heritage of Europa Science Objectives.**

| Committee | Report Title | Ref. |
|---|---|---|
| Europa Orbiter Science Definition Team | Europa Orbiter Mission and Project Description | 19 |
| Committee on Planetary and Lunar Exploration (COMPLEX) | A Science Strategy for the Exploration of Europa | 20 |
| NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System | Europa and Titan: Preliminary Recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System | 21 |
| Solar System Exploration ("Planetary Science Decadal") Survey | New Frontiers in the Solar System: An Integrated Exploration Strategy | 22 |
| Jupiter Icy Moons Orbiter (JIMO) Science Definition Team | Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO) | 23 |
| Europa Focus Group of the NASA Astrobiology Institute | Europa Science Objectives | 24 |
| Outer Planets Assessment Group (OPAG) | Scientific Goals and Pathways for Exploration of the Outer Solar System | 25 |
| NASA Solar System Exploration Strategic Roadmap Committee | 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate | 26 |
| Europa Explorer 2007 Science Definition Team | 2007 Europa Explorer Mission Study: Final Report | 16 |

# 4. Assessment of Alternative Europa Mission Architectures

In the course of studying concepts for missions to Europa a number of candidate architectures have been considered, as shown in Figure 7. These include both single-element and multiple-element types. Single-element missions might consist of an orbiter around Europa, a Jupiter orbiter that makes multiple close passes by Europa during its mission, or a single flyby spacecraft, as in the Voyager and New Horizons missions. Architectures involving a single capable lander-only mission delivered by a simple cruise stage and communicating directly to Earth have not been studied yet in detail, for reasons given later in this section. Multiple-element missions might add a lander to an orbiter or flyby spacecraft, with the lander design ranging from a fully instrumented soft lander, to a more limited hard lander, to a simple impactor; multiple orbiting platforms might also be possible, maybe even sample return missions, but they have not been studied in detail, again for reasons given later in this section. One platform type, an aerial vehicle (e.g., a balloon), is rejected after only cursory consideration. The Europan atmosphere is so tenuous it is difficult even to *detect* with all but the most sensitive of instruments. Its mass density is orders of magnitude too small to cause detectable aerodynamic drag on orbiting spacecraft or impactors, let alone support any kind of aerial vehicle, so it need not be considered.

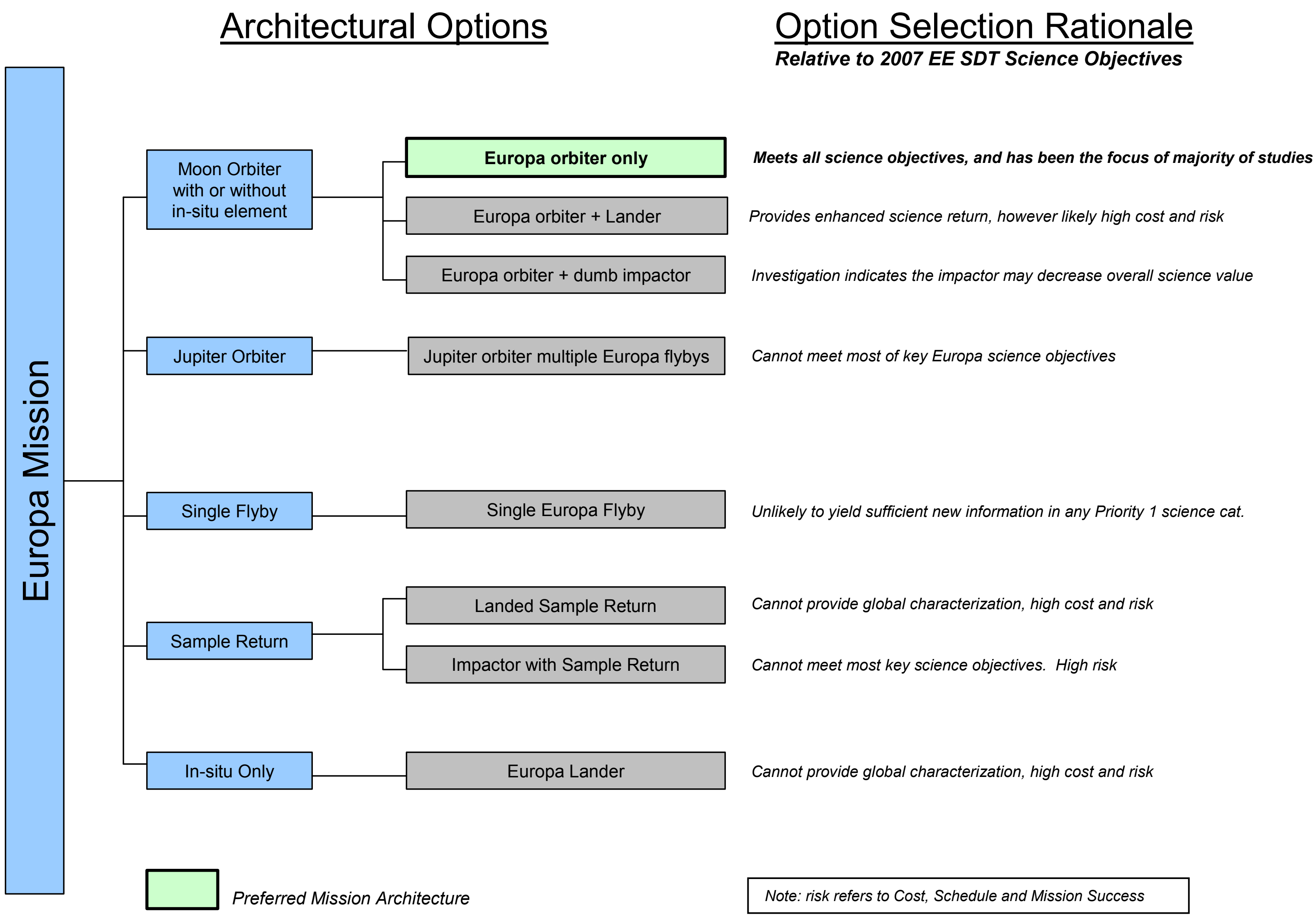


**Figure 7. Architecture Options.**

Previous studies have examined all these applicable options, with varying science objectives and in greatly varying levels of detail. Reviewing the implications of these architectures in light of current Europa science objectives, as summarized in Table 4 [16], and considering technological readiness, cost and risk, the choice of optimal mission architecture quickly narrows to a dedicated Europa orbiter mission. The EE mission concept, such a dedicated orbiter mission, fully addresses all of the science objectives defined by the 2007 EE SDT and has been the focus of most of the recent studies for Europa exploration. The remainder of this section addresses the characteristics of the multiple-element architectures, and then the alternative single-element architectures, that make them less attractive than the single-orbiter-only option for a first dedicated mission to Europa. Further assessment would need to be done to address the impact of planetary protection requirements on mission cost, design, mass, and schedule for landers and sample return missions, as this study does not address planetary protection considerations.

**Table 4. Architectures considered and rated against the Priority 1 Europa Science Objectives.** ***(after Pappalardo et al., 2007)***

| | A. Ocean | B. Ice | C. Chemistry | D. Geology | E. External Environment |
|---|---|---|---|---|---|
| **Europa Explorer** | 5 | 5 | 5 | 5 | 5 |
| **Europa Explorer + Simple Lander** | 6 | 6 | 6 | 6 | 5 |
| **Europa Multiple Fly-bys** | 2 | 2 | 2 | 3 | 3 |
| **Capable Lander (No Orbiter)** | 3 | 2 | 4 | 2 | 1 |

**NOTES:**

- Multiple fly-bys means a dedicated Europa fly-by mission.
- Orbiter + lander implies a simple lander, carrying a seismometer, imager, composition experiment.
- Capable Lander is stand-alone (no orbiter), modeled after the Europa Astrobiology Lander.

| | |
|---|---|
| 6 | Exceeds science objectives. |
| 5 | Fully addresses all science objectives. |
| 4 | Addresses most science objectives. |
| 3 | Addresses some science objectives. |
| 2 | May address partial science objectives. |
| 1 | Touches on science objectives. |
| 0 | Does not address science objectives. |

## 4.1 Moon Orbiter, Plus Lander or "Dumb" Impactor

The addition of a simple instrumented lander to a Europa orbiter mission would provide even greater science return, exceeding the EE SDT's science objectives in all but one category [16] (see Table 4, row 2). Such a mission architecture would enable global remote sensing with ground truth for at least one site on the surface, and science measurements not possible from an orbiter. Given the likelihood of significant Europan tidal flexing, levels of seismic activity should be of sufficient magnitude that *in situ* measurements would provide unique geophysical insight into the subsurface and interior. Although costs have not been accurately modeled for any landed systems, the EE study determined that the cost for an orbiter with even a simple soft lander would likely exceed the expected resources available [16]. Moreover, the inferred low technology readiness of a simple hard lander, especially one landing on a surface whose topography is not well characterized, suggests a high risk to schedule and cost.

Multiple design teams have concluded that the only practical means of reducing the risk of safe landing on Europa, in a time frame consistent with implementation of the lander, is high-resolution imaging characterization of the surface, especially potential landing sites, from a precursor orbiter mission. Imaging of the candidate landing sites from an orbiter that delivers the lander is not useful, since the new information is not available for the design of the lander, and there is no guarantee that an orbiter with a lander designed for specific surface characteristics will find any scientifically interesting area, or any area at all, with those characteristics. It is an appropriate role for an orbiter mission to provide the information that enables subsequent lander missions with acceptable levels of risk.

A simple "dumb" impactor added to a Europa orbiter or flyby mission could allow remote measurement of elemental composition from the impact flash, and would excavate material from the shallow subsurface that might not have been radiolytically processed, for remote analysis later. However, a preliminary assessment by the EE team of the impact energies for reasonable masses and velocities suggest that the crater formed would be too small to yield significant compositional measurements, and might be too small to locate [16]. Instruments optimized for the Europa Priority 1 science objectives are different from the specialized instrumentation needed to observe an impact flash and plume, implying additional cost and/or the loss of other science.

### 4.2 Multiple Moon-Orbiting Platforms

Multiple orbiting platforms, in the form of an orbiting subsatellite deployed from a primary orbiting spacecraft, have several avenues for augmenting the science from a single orbiter, but would have significant impact on the resources available for the primary orbiter. At Europa, as elsewhere, simultaneous measurements from multiple spacecraft improve magnetospheric investigations. But according to the EE SDT, the greatest science gain would stem from formation-flying gravity measurements [16] as done by the GRACE mission at Earth [27]. Such investigations would primarily target the high-degree and -order (short spatial scale) gravity field components. But the measurable tidal signal of an internal Europan ocean is low-order (degree 2), and the most likely sources of non-isostatically–compensated gravity field anomalies are sufficiently deep, below the icy shell and ocean, that the higher-order signal levels would be quite feeble at orbital altitudes. Thus, the science gain from such a subsatellite would be limited. But the impact on resources for the primary orbiter would be substantial: the subsatellite would have to duplicate many of the subsystems of the primary orbiter, such as power, attitude determination and control, communications, command and control, etc., in addition to the subsatellite's payload. Resources devoted to the subsatellite, especially mass and cost, would subtract from those available to the primary orbiter and its payload. The EE SDT determined that a subsatellite's science did not justify the added cost and complexity [16].

### 4.3 Multiple Flybys

A Jupiter orbiter with multiple close flybys of Europa could provide significant science return to address some of the key science objectives for Europa. However, important measurements related to the ocean and other objectives cannot be achieved except from orbit. A flyby mission cannot provide 1) gravity and altimetry data of the requisite accuracy measured at appropriate phases of the tidal cycle, addressing the ocean objective; 2) significant areal coverage by an ice-penetrating radar for the ice shell objective; 3) global and targeted spectral imaging coverage at high resolution for the chemistry and geology objectives; and 4) sufficient temporal and spatial coverage for the external environment objective [16]. The Jupiter System Observer (JSO) flagship mission concept, studied by another team in parallel with the 2007 EE study, would do Europa science in the multiple-flyby fashion, with a many-flyby tour of the Galilean satellites that would include 6 or more Europa flybys. The 2007 EE SDT reviewed the JSO approach's performance in achieving its Europa science objectives and concluded that JSO would do a "poor" job, addressing less than 50% of the high-priority objectives.

Some have wondered if a Juno-like spacecraft and mission could perform Europa flyby science. But the JSO mission would provide far better science than would a Juno-like mission. To provide the best science possible by keeping encounter velocities low, the JSO mission concept's orbit would be fairly narrowly constrained to Jupiter's equatorial plane, with only small excursions to adjust flyby geometries. Of the many JSO flybys, the best for science occur in low-eccentricity orbits with low flyby V-infinities. The Juno mission's highly eccentric polar orbit [28] will be much less amenable to satellite science. It is such an orbit that will keep Juno's radiation dose relatively low for the first 20 (or so) orbits, despite a perijove within about 1.1 Jovian radii. Near perijove, that orbit will thread an axially aligned, roughly cylindrical "clear zone" between the planet and the inside edge of the main radiation belts, then recross the equatorial plane well outside the roughly toroidal ("doughnut-shaped") radiation belts. Jupiter's oblateness, notably the large $J_2$ component of its gravity field, will cause the eccentric polar orbit's line of apsides to rotate with each perijove pass, such that eventually the "long sides" of the ellipse will pass briefly near each of the Galilean satellites. But the flyby V-infinities for such an approach to Europa will be far greater than would be for JSO, more than 20 km/s compared to JSO's less than 10 km/s. Attempting to decrease the flyby velocities by rotating the Juno orbit into the equatorial plane would thwart the "threading" approach and result in radiation fluxes even greater than JSO would receive during its orbit insertion maneuver, just inside Io's orbit. The Juno spacecraft is not designed to survive this increased radiation level. For multiple reasons, the Juno approach is not suitable for a Europa mission.

### 4.4 Single Flyby

The single-flyby option was dismissed from further consideration because it is unlikely to yield significant new information in *any* of the highest-priority Europa science objective categories. This conclusion is consistent with a similar conclusion by the "Billion Dollar Box" study [29] of potential missions to Saturnian icy satellites Titan and Enceladus. The general conclusion that it is difficult to justify a single-flyby mission at a satellite already visited multiple times by a well-instrumented spacecraft orbiting the satellite's primary would not be a surprise. In the case of Europa, multiple Galileo flybys "raise the bar" for significant science there.

### 4.5 Stand-Alone Lander

A large stand-alone lander carrying a full suite of instruments for surface science could provide significant new results for Europa, especially if it were long-lived (more than 5 eurosols or 18 days). While the science return from a capable surface lander could be high, a lander would characterize only one location on Europa, which would not necessarily be representative of the satellite as a whole. At the current stage of Europa exploration, science priorities focus on global characterization, which would not be provided by a lander at a single location. Thus, a capable lander without a supporting orbiter does not address the Europa Explorer SDT's science objectives well. Moreover, the technology readiness of such a lander is quite low, and the surface topography of Europa is unknown at scales of concern to landers, posing significant problems for a safe landing. A capable lander is anticipated to have a high risk and cost.

### 4.6 Sample Return

Planetary scientists have emphasized for decades the benefits of bringing samples of extra-terrestrial materials to Earth, where the full power and flexibility of huge ground-based laboratories can be brought to bear on the analyses of the samples. The role of the Apollo samples in unraveling the origin of Earth's moon is a prime example. But despite the potential paradigm-altering science return, sample return missions to outer solar system destinations must contend with three significant hurdles: long mission durations for a round-trip to a distant location; risk that the required samples might not be collected or delivered to a useful location such as a curation facility on Earth; and high cost. Note that these are common challenges, and a specific mission could also face other challenges.

The proposed Europa Ice Clipper [30] mission is a sample return mission concept based on an interesting variation on the single flyby spacecraft. In this architecture a flyby spacecraft would release an impactor on approach to Europa. The impactor would create a crater and plume of debris through which the spacecraft would fly, collecting debris samples as it passes through. The samples would then be returned to Earth. While such a mission has the potential for returning unique results, it has problems with both science value and technical risk: it can address only a limited number of Europa science objectives at a single impact site, and is generally considered high risk for a number of reasons, including a low probability of obtaining an acceptable sample coupled with extremely demanding navigation requirements. The closer to Europa's surface the sample collecting spacecraft flies in an effort to increase the (small) chance of acquiring a usable sample, the tighter are the navigation requirements to prevent a catastrophic impact of the spacecraft on Europa's surface.

A more "conventional" landed sample return mission, one that places a soft-lander on the surface to collect and document samples, suffers greatly from the mission duration and cost problems. Compared to the Ice Clipper architecture, the landed sample return mission involves much more delta-V and thus more mass, time, and cost, and a much more complex flight system that is far more costly. A previous study by Woodcock [31], and preliminary results of a current study by some of this study's authors [32], of the utility of the proposed Ares launch vehicles for solar system exploration indicate that launching a landed outer solar system sample return mission appears to be a job for an Ares V launch vehicle, with an anticipated unit cost over $1B. It is clear that this type of sample return mission would far exceed the fiscal resources expected to be available for a flagship mission in the relatively near future.

### 4.7 Most Appropriate Architecture

A single Europa orbiter with no lander, impactor, or subsatellite is the architecture of choice for a first dedicated mission to Europa, since it fully addresses the science objectives at the lowest risk and cost, and since it provides the information needed to enable a future Europa lander with acceptable risk.

# 5. Conclusions

The objective of this study, *to assess the science merit, technical risk and qualitative assessment of relative cost of alternative architectural implementations as applied to a first dedicated mission to Europa,* was accomplished by 1) reviewing results from previous and current studies and 2) examining alternative architectural options relative to the science objectives defined by the 2007 EE SDT. This report summarizes a number of Europa mission and system concepts studied over the last decade as well as the results from assessing alternative architectural options in light of current science requirements. Based on this work, the study arrived at the following conclusions:

1. A dedicated orbiter mission to Europa provides the greatest science value (as measured by the 2007 EE SDT science objectives) at lowest risk. This conclusion is consistent with the conclusions of previous studies.

2. Varying programmatic constraints and evolving prioritization of science objectives affected the details of studies over the last decade but not the high-level conclusions.

# 6. References


[1] "Europa Orbiter", Team X Final Report, July 12, 1996. (JPL internal document)

[2] "Europa Orbiter, Pluto Spacecraft Option", Team X Final Report, July 12, 1996. (JPL internal document)

[3] "Europa Sample Return", Team X Final Report, June 25, 1996. (JPL internal document)

[4] "Europa Orbiter, All Solar," Advanced Projects Design Team (Team X), Final Report, 2 June 1997. (JPL internal document)

[5] Europa All-Solar Revisit, JPL IOM 311.1/98-5, May 29, 1998NS. (JPL internal document)

[6] Europa Orbiter Overview 7-9-01 (ppt). (JPL internal document)

[7] Europa Orbiter Alternative Missions Study, JPL Advanced Mission Studies Office, 8-15-01. (JPL internal document)

[8] "Europa Orbiter Competitive", Team X Final Report, October, 2002. (JPL internal document)

[9] Jovian Icy Moons Tour Mission Studies, Final Report, February 28, 2003. (JPL internal document)

[10] Nuclear Systems Initiative (NSI) Jovian Icy Moon Tour Mission Study Non-Fission Dual Cruisers to the Jovian Moons Flight System, January 27, 2003.

[11] Prometheus Project Final Report, Doc No. 982-R120461, October 1, 2005. (JPL internal document)

[12] (a) Europa Geophysical Explorer Mission Concept Study, JPL internal document D-32355, September 30, 2005 (b)Europa Explorer Design Team Report, JPL internal document D-34109, April 27, 2006.

[13] Europa Explorer Study Report, JPL internal document D-34054, March 10, 2006.

[14] Europa Explorer Solar Array Feasibility Report, August 30, 2006. (JPL internal document)

[15] Enhanced Europa Geophysical Explorer Study (EEGE) utilizing Advanced Radioisotope Power System, October 2006. (JPL internal document)

[16] 2007 Europa Explorer Mission Study: Final Report, JPL internal document D-41283, 1 November, 2007. Cleared for external release.

[17] Solar-Powered Europa Orbiter Design Study (2007), JPL internal document D-40344, September 28, 2007. Cleared for external release as JPL Pub 08-2, January 2008.

[18] Europa Surface Science Package Feasibility Assessment, JPL internal document D-30050, September, 2004.

[19] NASA AO: 99-OSS-04, Europa Orbiter Mission and Project Description, 1999.

[20] COMPLEX, Committee on Planetary and Lunar Exploration (1999), National Research Council, *A Science Strategy for the Exploration of Europa*, National Academy Press, Washington, DC.

[21] Chyba, C. F., W. B. McKinnon, A. Coustenis, R. E. Johnson, R. L. Kovach, K. Khurana, R. Lorenz, T. B. McCord, G. D. McDonald, R. T. Pappalardo, M. Race, and R. Thomson (1999), Europa and Titan: Preliminary recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System. *Lunar Planet. Sci. Conf.*, *XXX*, abstract #1537, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

[22] SSES, Solar System Exploration Survey (2003), Space Studies Board, National Research Council, New Frontiers in the Solar System: An Integrated Exploration Strategy, National Academy Press, Washington, D.C.

[23] JIMO SDT, Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO) (2004), NASA, Washington, D.C., 2004. <http://www.lpi.usra.edu/opag/resources.html>

[24] Pappalardo, R. (2006), Europa Science Objectives, NAI Europa Focus Group (Report to OPAG), <http://www.lpi.usra.edu/opag/may_06_meeting/agenda.html>.

[25] OPAG, Outer Planets Assessment Group (2006), Scientific Goals and Pathways for Exploration of the Outer Solar System, <http://www.lpi.usra.edu/opag>.

[26] SSER, Solar System Exploration Roadmap (2006), NASA Science Mission Directorate. <http://solarsystem.nasa.gov/multimedia/downloads/SSE_RoadMap_2006_Report_FC-A_med.pdf>

[27] NASA, "Gravity Recovery and Climate Experiment", Science@NASA website, <http://science.hq.nasa.gov/missions/satellite_19.htm>

[28] Matousek, Steve, "The Juno New Frontiers Mission", *Acta Astronautica*, Volume 61, Issue 10, November 2007, Pages 932–939.

[29] Reh, K. R. et al., Titan and Enceladus $1B Mission Feasibility Study, Prepared for NASA's Planetary Sciences Division, Performed at JPL, Final Report JPL D-37401B posted on the OPAG website: <http://www.lpi.usra.edu/opag/announcements.html> as "$1B Box Studies", January 30 (2007).

[30] "Europa Ice Clipper Summary", excerpt from 1997 Discovery Proposal, posted on the Astrobiology Web site: <http://www.astrobiology.com/europa/clipper/index.html>

[31] Woodcock, G., Ares Report, Prepared for David B. Smith (Boeing Company), PowerPoint presentation, December 13 (2007).

[32] "Ares V: Application to Solar System Scientific Exploration", JPL D-41883, December 12, 2007. Cleared for external release as JPL Pub 08-3.

# 7. Glossary

| | |
|---|---|
| AMTEC | Alkali Metal Thermal to Electric Converter |
| ARPS | Advanced Radioisotope Power Systems |
| BOL | Beginning of Life |
| COMPLEX | Committee on Planetary and Lunar Exploration |
| Delta IVH | Delta IV Heavy |
| Delta-V | Delta Velocity |
| EDL | Entry, Descent and Landing |
| EE | Europa Explorer |
| EEGE | Enhanced Europa Geophysical Explorer |
| EGE | Europa Geophysical Explorer |
| EIS | Europa Integrated Science package |
| EO | Europa Orbiter |
| GPHS | General Purpose Heat Source |
| GRACE | Gravity Recovery and Climate Experiment |
| IUS | Inertial Upper Stage |
| JIMO | Jupiter Icy Moons Orbiter |
| JIMT | Jupiter Icy Moons Tour |
| JSO | Jupiter System Observer |
| LEO | Low Earth Orbit |
| LV | Launch Vehicle |
| MMRTG | Multi-Mission Radioisotope Thermoelectric Generator |
| NEP | Nuclear Electric Propulsion |
| NEXT | NASA Evolutionary Xenon Thruster |
| NSI | Nuclear Systems Initiative |
| OPAG | Outer Planets Assessment Group |
| REP | Radioisotope Electric Propulsion |
| RHU | Radioisotope Heater Unit |
| RPS | Radioisotope Power System |
| RTG | Radioisotope Thermoelectric Generator |
| S/C | Spacecraft |
| SDT | Science Definition Team |
| SEP | Solar Electric Propulsion |
| SMM | Science Mission Module |
| SRMU | Solid Rocket Motor Upgrade |
| STS | Space Transportation System (Space Shuttle) |
| Team X | JPL's Advanced Projects Design Team (concurrent engineering) |
| VEEGA | Venus Earth Earth Gravity Assist |

# 8. Europa Quick-Look Statistics

| | |
|---|---|
| Discovery | Jan 7, 1610 by Galileo Galilei |
| Diameter (km) | 3,138 |
| Mass (kg) | 4.8e22 kg |
| Mass (Earth = 1) | 0.0083021 |
| Surface Gravity (Earth = 1) | 0.135 |
| Mean Distance from Jupiter (km) | 670,900 |
| Mean Distance From Jupiter (Rj) | 9.5 |
| Mean Distance from Sun (AU) | 5.203 |
| Orbital period (days) | 3.551181 |
| Rotational period (days) | 3.551181 |
| Density (gm/cm$^3$) | 3.01 |
| Orbit Eccentricity | 0.009 |
| Orbit Inclination (degrees) | 0.470 |
| Orbit Speed (km/s): | 13.74 |
| Escape velocity (km/s) | 2.02 |
| Visual Albedo | 0.64 |
| Surface Composition | Water Ice |

http://www2.jpl.nasa.gov/galileo/europa/